FOCUSING OPTICS FOR SMALL SPOT OPTICAL METROLOGY

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5 **Priority Claim:**

The present application claims priority to U.S. Provisional Patent Application Serial No. 60/429,152, filed November 26, 2002, which is incorporated herein by reference

Technical Field

10   This invention relates to optical tools for measuring and evaluating semiconductor wafers. In particular, the present invention relates to objectives used to focus light onto semiconductor wafers and to gather light reflected by semiconductor wafers as part of a measurement process.

15 **Background of the Invention**

As semiconductor geometries continue to shrink, manufacturers have increasingly turned to optical techniques to perform non-destructive inspection and analysis of semiconductor wafers. Techniques of this type, known generally as optical metrology, operate by illuminating a sample with an incident field (typically referred to as a probe beam)

20 and then detecting and analyzing the reflected energy. Ellipsometry and reflectometry are two examples of commonly used optical techniques. For the specific case of ellipsometry, changes in the polarization state of the probe beam are analyzed. Reflectometry is similar, except that changes in intensity are analyzed. Scatterometry is a specific type of optical metrology that is used when the structural geometry of a sample creates diffraction (optical

25 scattering) of the probe beam. Scatterometry systems analyze diffraction to deduce details of the structures that cause the diffraction to occur.

Various optical techniques have been used to perform optical scatterometry. These include broadband spectroscopy (U.S. Patent Nos. 5,607,800; 5,867,276 and 5,963,329), spectral ellipsometry (U.S. Patent No. 5,739,909) single-wavelength optical scattering (U.S.

30 Patent No. 5,889,593), and spectral and single-wavelength beam profile reflectance and beam profile ellipsometry (U.S. Patent No. 6,429,943). Scatterometry, in these cases generally

refers to optical response information in the form of diffraction orders produced by periodic

structures (e.g., gratings on a wafer). In addition it may be possible to employ any of these

measurement technologies, e.g., single-wavelength laser BPR or BPE, to obtain critical

dimension (CD) measurements on non periodic structures, such as isolated lines or isolated

5   vias and mesas. The above cited patents and patent applications, along with PCT Application

WO03/009063, US Application 2002/0158193, US Application 2003/0147086, US

Application 2001/0051856 Al, PCT Application WO 01/55669 and PCT Application WO

01/97280 are all incorporated herein by reference.

As shown in Figure 1, a typical optical metrology system includes an illumination

10   source that creates a monochromatic or polychromatic probe beam. The probe beam is

projected by one or more lenses onto the surface of a sample. The portion of the sample

surface that is illuminated by the probe beam is referred to as the illumination spot. The

sample reflects the probe beam and the reflected probe beam (or a portion of the reflected

probe beam) is transported to a detector. For most systems, the detector gathers energy from

15   a small area within the sample surface known as the measurement spot. The measurement

spot may be smaller or larger than the illumination spot. The detector transforms the energy

it receives into corresponding output signals. A processor analyzes the signals to measure

the structure or composition of the sample. For cases where the probe beam is

polychromatic, the detector is often preceded by an optical element that disperses the

20   incoming probe beam into different wavelengths. A prism or grating may be used for this

purpose. This allows different portions of the detector to measure different spectral

components of the reflected probe beam off the sample. In these cases, the combination of

the spreading optical component and the detector is generally referred to as a spectrometer.

The decreasing size of semiconductor geometries forces metrology to analyze

25   increasingly small areas. In practice, the area being measured is typically a test feature that is

often less than 50µm wide and is often surrounded by a completely different material or film

stack. Accurately analyzing small areas requires that the illumination spot and the

measurement spot be relatively small. This, in turn requires that the incoming and reflected

probe beams be tightly focused to support small spot sizes.

30   One way of meeting these requirements (at least partially) is by using small angles of

incidence for the incoming and reflected probe beams. Small angle of incidence systems

reduce the amount by which the sample projects the illumination and measurement spots. This is one of the main motivations behind metrology systems of the type shown in Figure 2 in which the incoming and reflected probe beams are directed normally to the sample surface. As may be appreciated, the use of normal incidences means that the illumination

5   and measurement spots have a circular cross-section. The circular cross-section is effectively smaller than the elliptical cross-section associated with non-normally directed beams.

In systems where normal incidence is used (e.g., the system of Figure 2) the focusing assembly transports both the incident and the reflected probe beam. This differs from non-normal systems where distinct optical components are used for incident and reflected probe

10   beams. Several focusing assemblies have been developed for this purpose. These focusing assemblies can be formed from refractive or reflective elements or a combination of refractive and reflective elements. Of the different designs, refractive designs are attractive because they have no central and peripheral [e.g., spider arms] obscurations that may cause scattering within the metrology tool. Unfortunately, chromatic aberrations are inherent in

15   refractive optics. Minimizing such aberration over the wavelength range of DUV to IR is difficult while maintaining small spot sizes.

It is another common practice to use rotationally symmetric reflective designs such as Schwarzschild microscope objectives. As shown in Figure 3, a classical Schwarzschild objective consists of a large primary concave and a small secondary convex mirror system in

20   which the two mirrors are or nearly monocentric. The two mirrors form a path between an illumination source or a detector (or both) and the surface of a sample. Unfortunately, the secondary mirror forms a central obscuration and secondary mirror hardware support structures form spider arm obscurations. The central obscuration blocks useful probe beam at and near zero numerical aperture and increases diffraction effects. Further, the spider arm

25   obscurations introduce scatters as a function of spider arms geometry which is undesirable when measuring patterned structures.

Summary of the Invention

The present invention includes a system for focusing broadband light within an ellipsometer, reflectometer or other optical metrology tool. One implementation of the focusing system uses a two-mirror system. A concave spherical mirror is used to gather light

5   from the surface of a sample under inspection. The concave spherical mirror projects the received light to a convex spherical mirror. The combination of the two mirrors captures the light diverging from the sample and collimates the light into parallel rays. The light can then be passed through an aperture stop prior to entering a detector.

Each of the mirrors is an off-axis section of a parent spherical mirror. The two parent

10   mirrors are monocentric or nearly monocentric (i.e., they have the same or nearly the same center of curvatures). The aperture stop is located at or near one of the mirrors, (i.e. pupil-centric design). This design utilizes the beneficial monocentric and pupil-centric properties of the parent mirrors and can be substantially free of third order spherical aberration, coma and astigmatism and chromatic aberration. The mirror radii are chosen for small focal spot.

15   The mirror offsets and spacing are chosen to avoid beam obscuration. Additional optics may be added to the base design to achieve telecentricity or improve spot size or achieve desired probe beam incidence angle at the sample. This design obtains many of the benefits of a conventional Schwarzschild design without the associated diffraction effects of a central obscuration.

20   A second implementation of the focusing system replaces the convex spherical mirror with a flat mirror. The concave spherical mirror is replaced with an off axis paraboloid mirror. In either implementation, the focusing system may be placed on the illumination side or collection side of a reflectometer or other optical metrology tool.

Brief Description of the Drawings

25   Figure 1 is a block diagram of a prior art optical metrology system.

Figure 2 is a block diagram of a prior art optical metrology system in which the incident and reflected beams are normally directed with respect to the sample.

Figure 3 shows a prior art Schwarzschild microscope objective.

Figure 4A shows a first implementation of a focusing system as provided by the

30   present invention.

Atty Docket No. TWI-23310

Figure 4B is a perspective view of the focusing system of Figure 4A.

Figure 5 is a computer generated plot showing the illumination or measurement spots and field height generated by the focusing system of Figure 4.

Figure 6A shows a second implementation of a focusing system as provided by the

5   present invention.

Figure 6B is a perspective view of the focusing system of Figure 6A.

Figure 7 is a computer generated plot showing the illumination or measurement spots and field height generated by the focusing system of Figure 6.

Detailed Description of the Preferred Embodiments

The present invention includes a system for focusing broadband light within an ellipsometer, reflectometer or other optical metrology tool. One possible implementation for the focusing system is shown in Figure 4A and 4B with the general designation 400. For this

5   particular example, focusing system 400 is used on the collection side of an ellipsometer or . reflectometer and is used to transport light from a sample 402 to a detector 404. Focusing system 400 may also be used on the illumination side of a metrology system to transport light from an illumination source to the surface of sample 402.

As shown in Figure 4A, light reflected by sample 402 is collected by a concave

10   spherical mirror 406. Spherical mirror 406 projects the received light to a convex spherical mirror 408. The combination of the two mirrors 406, 408 captures the light diverging from sample 402 and collimates the light into parallel rays 412. The light can then be passed through an aperture stop 410 prior to entering detector 404. Rays 412 are parallel specifically to support the case where focusing system 400 is used within a system (such as

15   an ellipsometer) that includes a rotating compensator. For other systems, it is possible to fabricate mirrors 406, 408 so that rays 412 are not parallel.

Each of mirrors 406, 408 is an off-axis section of a parent spherical mirror. Mirrors 406, 408 are positioned as if their parents were monocentric or nearly monocentric (i.e., they have the same or nearly the same center of curvatures). Aperture stop 410 is

20   located at or near one of the mirrors 406, 408 (i.e. pupil-centric design). This design utilizes the beneficial monocentric and pupil-centric properties of the parent mirrors and can be substantially free of third order spherical aberration, coma and astigmatism and chromatic aberration. The mirror radii are chosen for small focal spot. The mirror offsets and spacing are chosen to avoid beam obscuration. Additional optics may be added to the base design to

25   achieve telecentricity or improve spot size. This design obtains many of the benefits of a conventional Schwarzschild design without the associated problem of a central obscuration.

Focusing system 400 has the following characteristics:

1.   Small axial focal spot (<< 50um).

2.   No chromatic aberration.

3.   Significantly reduced spherical aberration (system is monocentric or near

5   monocentric).

4.   Significantly reduced coma or astigmatism (system is or near pupil centric).

5.   No central obscuration.

6.   Spherical mirror surfaces can be classically polished to a low surface

       roughness.

10   7.   Mirror surfaces have low scatter since no diamond turning artifacts.

8.   Angle of incidence range is +/- 90 degrees.

The following table outlines one possible recipe for focusing system 400:

Surface	Radius	Thickness	Y-decenter	Notes
Object	Infinity	Infinity		Parallel ray 412
1	Infinity	0		
2	Infinity	0		
3	Infinity	32.51		
Stop	Infinity	0		Aperture stop 410
5	Infinity	0	22	Displacement from parent of 408
6	43.296	-32.51		Reflective mirror 408
7	73.129	32.51		Reflective mirror 406
8	Infinity	80.08		
Image	Infinity	0		Sample 402
Effective Focal Length = 45.0				
F/Number = 4.5				

Figure 5 shows the spots sizes and field heights that can be achieved using the recipe

15   in the preceding table. As shown in the lowermost portion of that figure, the axial spot size is

substantially less than 50μm. This spot size is achieved over the wavelength range of 190nm

to 900nm. The middle and upper portions show the spot sizes at +0.1 degrees and –0.1

degrees, respectively.

As mentioned previously, focusing system 400 can be used for either collection or

20   illumination. It is also possible to use focusing system 400 to provide both collection and

illumination to the sample. . This is accomplished by rotating focusing system 400 with respect to sample 402, so the incident and reflected probe beams have substantially normal incidence angle at sample 402. One or more flat mirrors may be added to focusing system 400, typically before mirror 406 or after mirror 408, so rays 412 and beam reflected off

5   sample 402 are parallel, for purpose of packaging. A beam splitter is then used to is then used to simultaneously direct the probe beam output of an illumination source to mirror 408 (and on to sample 402) while allowing the returning probe beam to enter detector 404.

A second possible implementation for the focusing system is shown in Figure 6A and 6B with the general designation 600. For this particular example, focusing system 600 is

10   used on the collection side of an ellipsometer or reflectometer and is used to transport light from a sample 602 to a detector 604. Focusing system 600 may also be used on the illumination side of a metrology system to transport light from an illumination source to the surface of sample 602. In either case, the angle of incidence (or reflection) is substantially normal. This is the typical mode of operation to support normal incidence reflectometry,

15   although it is also possible to use the illumination system 600 in non-normal applications.

As shown in Figure 6A, light reflected by sample 602 is collected by a concave off-axis paraboloid mirror 606. Parabaloid mirror 606 collimates the received light and projects the received light to a flat mirror 608. Mirror 608 redirects the light to be substantially parallel to the reflected probe beam at sample 602. The combination of the two mirrors 606,

20   608 captures the light diverging from sample 602 and collimates the light into parallel rays 612. The light can then be passed through an aperture stop 610 prior to entering detector 604. Rays 612 are parallel specifically to support the case where focusing system 600 is used within a system (such as an ellipsometer) that includes a rotating compensator. For other systems, it is possible to fabricate mirrors 606, 608 so that rays 612

25   are not parallel. It is also possible to replace paraboloid mirror 606 with an ellipsoidal, toriodal or generalized aspheric mirror, to achieve small focus spot with non-collimated rays 612.

Focusing system 600 has the following characteristics:

1.   Small axial focal spot (<< 50μm).

2.   No chromatic aberration.

3.   Significantly reduced spherical aberration.

4.   No central obscuration.

5.   Telecentric pupil.

6.   Angle of incidence range is +/- 90 degrees.

The following table outlines one possible recipe for focusing system 600:

Surface	Radius	Thickness	Conic	Alpha tilt	Y-decenter	Notes
Object	Infinity	Infinity				Parallel ray 612
1	Infinity	30				
Stop	Infinity	15				Aperture stop 610
3	Infinity	-21		20		Reflective mirror 608
4	Infinity	0			-26.2	
5	72	36	-1			Reflective mirror 606
6	Infinity	0		-40		
7	Infinity	0				
Image	Infinity	0				Sample 602
Effective focal length = 36.0						
F/Number = 4.5						

Figure 7 shows the spots sizes and field heights that can be achieved using the recipe in the preceding table. As shown in the lowermost portion of that figure, the axial spot size is substantially less than 50μm. This spot size is achieved over the wavelength range of 190nm to 900nm. The middle and upper portions show the spot sizes at +0.1 degrees and –0.1 degrees, respectively.

Aspheric constants:

$$Z = \frac{CY^2}{\sqrt{\left(1+\left(1-(1+K)\left(C^2\right)Y^2\right)\right)}} + \textit{higher order coefficients}$$

Z is surface sag, C is curvature, Y is semi-aperture and K is conic constant.

As mentioned previously, focusing system 600 can be used for either collection or illumination. It is also possible to use focusing system 600 to provide both collection and

illumination to the sample. Typically, this is accomplished by adding a beam splitter (or other optical device) between mirror 608 and detector 604. The beam splitter (not shown) allows the probe beam output of an illumination source to be directed to mirror 608 (and on to sample 602) while simultaneously allowing the returning probe beam to enter

5   detector 604.

The 45 degree off-axis paraboloid mirror 606 [with smaller NA and equivalently larger airy diameter] has much tighter encircled energy [total energy vs. distance from core] values than corresponding 20x objective. This is because of the central obscuration of typical 20x objective diffracts several percent of the light out of the core.

10   Focusing systems 400 and 600 can be scaled to any size or focal length and may be used in a range of metrology systems of which ellipsometers and reflectometers are only examples.